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METHODS OF STUDYING EARTHQUAKES

I PROPOSE in this paper to consider the methods of studying earthquakes of a moderate degree of intensity, *i. e.*, those which disturb areas of not more than a few thousands of square miles, and which as a rule are too weak to cause any very serious damage to property. Of such earthquakes, about ten or twelve are felt every year in Great Britian; the majority are slight, but once in four or five years a shock will occur that is noticed over a district containing more than 50,000 square miles. The methods of investigation do not, however, vary much in these cases; but, as they can only be applied with success in rather populous countries, it seems possible that they may be as useful in certain parts of the United States as they have already proved to be in the British Isles.

The whole aim of an earthquake inquiry has been widened during the last ten years. It is no longer merely a question of determining the position of the epicenter, though this is still one of the first problems to be solved. We have to ascertain not only the place where a fault-slip occurred, but the direction of the originating fault, its hade, and the nature of the movement which gave rise to the shock ; for the earthquake is but a passing incident in the growth of a fault. It is the transitory effect on the surface of a displacement, within the earth's crust; and the displacement, rather than its effect, is the more important subject for investigation.

For determining the position of the epicenter, three methods have been employed, depending respectively on observations of the direction, time of occurrence, and intensity of the shock.

The first method was suggested by Mallet, and used by him in studying the Neapolitan earthquake of 1857, and by a few other seismologists who have followed in his steps. Later on, the method fell into disrepute; and, so far as it depends on individual observations of the projection or fall of bodies, etc., it must, I think, be regarded as unreliable. But, if the number of observations be large, the average of all the records in one place may give a close approximation to the true direction. This was first shown by Professor Omori for the Tokio earthquake of 1894. In that city, the earthquake, besides a number of minor vibrations, consisted of a single great oscillation, the maximum displacement in which was 73^{mm} in the direction W. 20° S. and E. 20° N. Many columns and monuments were overthrown, and especially a large number of "Ishidoro" or stone lamp-stands placed in gardens. Professor Omori measured the directions in which 245 bodies fell in different parts of the city, 144 being "Ishidoro" with circular bases. The directions are extremely varied, and at first sight appear to be subject to no law, but the mean direction given by all the observations is W. 19° S. and E. 19° N.[1] If we take only the 144 "Ishidoro" with circular bases, and regard all the determinations of the direction as of equal value, we find the mean direction to agree exactly with that given by the seismographic record, and to have a probable error of less than two degrees.

The study of the Hereford earthquake of 1896 led to a somewhat similar result. In this case, observations of overturned bodies were not available, and the estimates of the direction were all made from personal impressions. They are extremely rough, few of the observers referring to more than the eight principal points of the compass. Moreover, as a general rule, the apparent direction of the movement was nearly perpendicular to one of the principal walls of the house in which the estimate was made. But this very fact, which seems to render the observations valueless, turns out to be of service; for the impression of direction is most distinct in buildings whose walls are perpendicular to the true direction of the shock. The majority of the records naturally come from such houses, and thus the average of all the estimates collected gives a nearly accurate result. The mean directions for London and Birmingham, for instance, intersect almost exactly in the epicenter, and those for several counties pass within a short distance of this spot.[1] Thus the method of directions, if we give a somewhat different meaning to it from that intended by Mallet, may determine the position of the epicenter with a close approach to accuracy.

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[1] Bull. della Soc. Sismol. Ital., Vol. II, 1896, pp. 180–188.

It is doubtful whether the second method, depending on time-observations, can ever lead to any but very rough results. The chief reason for this is the difficulty of determining the time accurately to within a few seconds. But, supposing this were possible, there is also the uncertainty whether it is the same phase of the motion which is timed by observers in different places; for the vibrations which appear strongest to different persons do not necessarily come from the same part of the focus, and may come from parts which are separated by a distance that is considerable when compared with the dimensions of the disturbed area. While good time-observations may enable us to determine the surface velocity of the earth-wave, they can hardly, unless very numerous, afford information of much value with regard to the position of the epicenter, and still less with regard to the depth of the focus.

There remains the third, and by far the most fruitful, method of inquiry — that which is founded on the intensity of the shock.

[1] "The Hereford Earthquake of 1896" (Cornish Bros., Birmingham,) pp. 265–270. I have applied this method to the Charleston earthquake of 1886, for which Captain Dutton's well-known memoir supplies the materials. Here it was necessary to group together observations in separate states, the areas of which are to large to give good results. But, in several cases, the mean direction so obtained differs only by a few degrees from the line joining the center of the state to the epicenter.

By means of an arbitrary scale, for which we are indebted to the joint labors of Professors M. S. de Rossi and F. A. Forel, the intensity at any place may be expressed according to the mechanical effects produced by the earthquake. A series of isoseismal lines may then be drawn, each surrounding the places where the shock was of a given intensity and excluding those where it was distinctly less; and if the series is complete, the innermost isoseismal enables us to determine the position of the epicenter, generally with a close approach to accuracy.

But the method of intensities does more than this. When the isoseismal lines are carefully drawn—and this is only possible roughly elliptical in form; their longer axes are parallel or nearly so, but they are not coincident. In my report on the Hereford earthquake (pp. 216–218), it is shown that this must be the case when the earthquake is due to the friction generated by a fault-slip; for the focus is then a surface inclined to the horizon. Moreover, the focus and relative positions of the isoseismal lines are indices of the direction and slope of the fault-plane. The longer axes of the curves are parallel to the fault-line or strike of the fault; and, on the side toward which the fault slopes, the isoseismal lines are further apart than on the other side of the fault-line, except at great distances in the case of a strong earthquake, when the inequality is reversed.

I can give no better example of a slight earthquake than that which occurred on April 1, 1898, in the south of Cornwall.[1] The positions of the principal places where it was felt are shown in Fig. 1, but the coast-line is omitted in order to simplify the diagram. The continuous curves represent the isoseismal lines of intensities 4 and 3 of the Rossi-Forel scale; and their forms and relative position show that the fault-line must run from E. 33° N. to W. 33° S., and that the fault must hade to the southeast.

The latter inference is corroborated by the study of the sound-phenomena, to which the two dotted lines relate. The outer of these lines represents the boundary of the sound-area, while the inner one separates those places where the sound was loud from those where it was distinctly fainter. As the more prominent sound-vibrations appear to come from the upper margin of the seismic focus[1], the northwesterly shift of the sound-curves with respect to the isoseismal lines implies that the fault hades in the direction opposite to them.

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[1] Quart. Jour. Geol. Soc., Vol. LXVI, 1900, pp. 1–7.

One of the most interesting features of British earthquakes, though it is by no means confined to them, is the double nature of the shock. At many places there are two distinct series of vibrations separated by a brief interval of absolute rest and with a large number of observations—they are as a rule quiet. This was the case during the Hereford earthquake of 1896 nearly all over the disturbed area. As a rule, however, a weak tremor and a faint rumbling noise are observed during the interval at places near the epicenter ; while at considerable distances from the origin these become imperceptible, and the shock appears to consist of two detached portions. The double shock is chiefly characteristic of strong or severe earthquakes but there are several slight ones in which it has been observed. Attempts have been made to explain it by the reflection or refraction of the earth-waves at the bounding surfaces of strata, or by the existence of longitudinal and transversal vibrations. But the wide distribution of the places where the double shock is observed and the fact that the relative nature of the two parts of the shock is not constant all over the

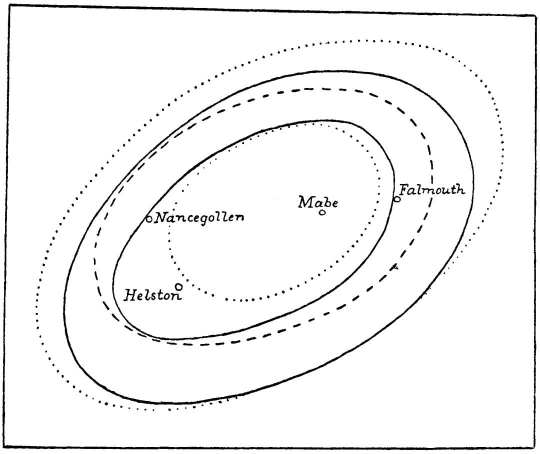

FIG. 1.

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[1] Phil. Mag., Jan. 1900, pp. 66–70.

disturbed area, are conclusive against any theory based on the assumption of a single initial impulse. In the cases which have been investigated, there can be no doubt, I think, that there were two distinct foci, and that the impulses at them were nearly, but not quite, simultaneous. In the Charleston earthquake of 1886, Captain Dutton was able to locate the two foci; and this has also been done in several British earthquakes.

There appear, however, to be two distinct classes of earthquakes in which a double shock is observed; of which the Cornish earthquake of 1898 and the Hereford earthquake of 1896 may be regarded as respective types. The chief outward difference consists in the length of the interval between the two parts of the shock. In the first case, the interval was a quarter of a minute or more in length; in the second, it varied from a few seconds to zero. The Cornish earthquake consisted in reality of two successive earthquakes originating in nearly the same region of the fault, and the foci were overlapping. The Hereford earthquake was a true *twin* earthquake, the foci were completely detached; but the impulses at the two foci were due to the same initial stress, and the impulse at the second was in no way a consequence of that at the first, for it took place before the earth-wave from the first had time to reach the other.[1]

The two parts of a twin earthquake differ as a rule in intensity, in duration, in the period of their vibrations, and possibly in other ways. The distribution of the places where the first part was stronger, etc., than the second, enable us to determine at which focus the initial impulse was the more powerful and which was first in action. In the Hereford earthquake, the region in which the first part of the shock was stronger, of greater duration, and consisted of slower vibrations, was separated from that in which the same features characterized the second part, by a hyperbolic band, passing between the two foci. Within this band the two parts of the shock were superposed, showing that the impulses were not simultaneous, and that the focus within the concave part of the hyperbola was last in action. In the Cornish earthquake of 1898, the interval between the two parts of the shock was so great that the first and weaker part was felt all over its disturbed area before the second was felt at its epicenter. Consequently, the broken line in Fig. 1, which surrounds all the places where the double shock was observed, constitutes the boundary of the disturbed area of the earlier portion.

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[1] The explanation of the double shock given in the report on the Hereford Earthquake (p. 295) I believe to be generally true for twin earthquakes; but I propose to consider the subject more fully in another paper.

In studying an earthquake, there will be found on almost every point considerable conflict in the evidence collected. Much of it is no doubt due to inaccurate observation, part to a misunderstanding as to the information desired. It is in the records of the sound phenomena that the greatest diversity exists, a diversity which can hardly be ascribed to inattention or defective observation, and which can only be explained completely on the supposition that the sound is so deep that some persons are incapable of hearing it. Near the epicenter, the strength of the sound-vibrations is so great that they are audible to nearly every person, but the percentage of observers who hear the sound decreases rapidly towards the boundary of the sound-area. The variation in audibility throughout the sound-area may be illustrated by means of isacoustic lines. The percentage of auditors of the sound among those observers within a given area who felt the shock is taken to correspond to the center of the area in question, the lines joining adjacent centers are divided so as to give points where the percentage would, on the hypothesis of uniform variation, have certain definite values, say 90, 80, 70, etc., and lines are drawn through all points where the percentage marked is the same. The isacoustic lines for the Hereford earthquake of 1896 are represented in Fig. 2. The axis of the isoseismal lines runs almost exactly northwest and southeast, and the points of greatest extension of the isacoustic lines lie on a curve (broken in the figure) which coincides almost exactly with the hyperbolic band referred to above. The explanation of the peculiar distortions of the isacoustic lines is that, along this band, the sound-vibrations from both foci were heard simultaneously, and the additional strength thus rendered them audible to an increased percentage of observers.[1]

The variation of other phenomena may be similarly represented — such as the frequency of comparison of the sound to

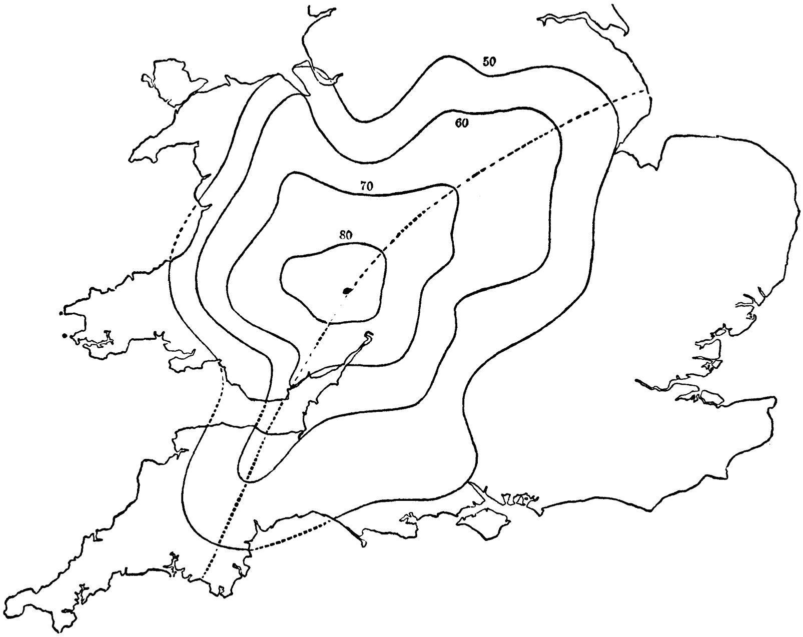

FIG. 2.

definite types, the audibility of the sound-vibrations before and after the shock is felt, the audibility of the loud crashes heard when the sound is loudest, etc. The method of course requires a very large number of records for its employment; but, in no other way, can the influence of erroneous or defective observations be so successfully eliminated.

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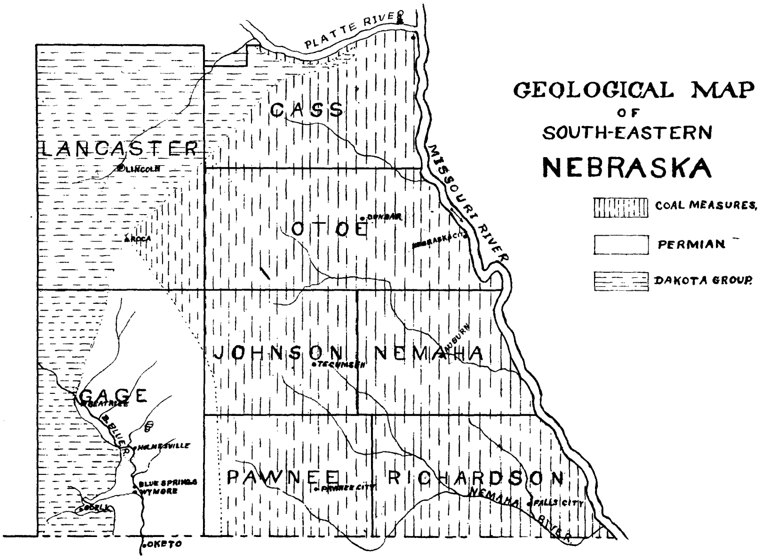
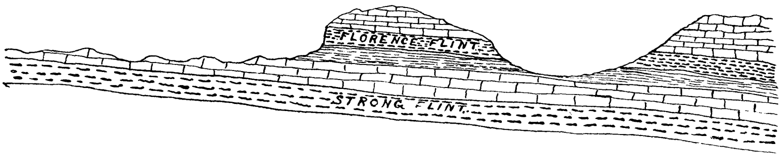
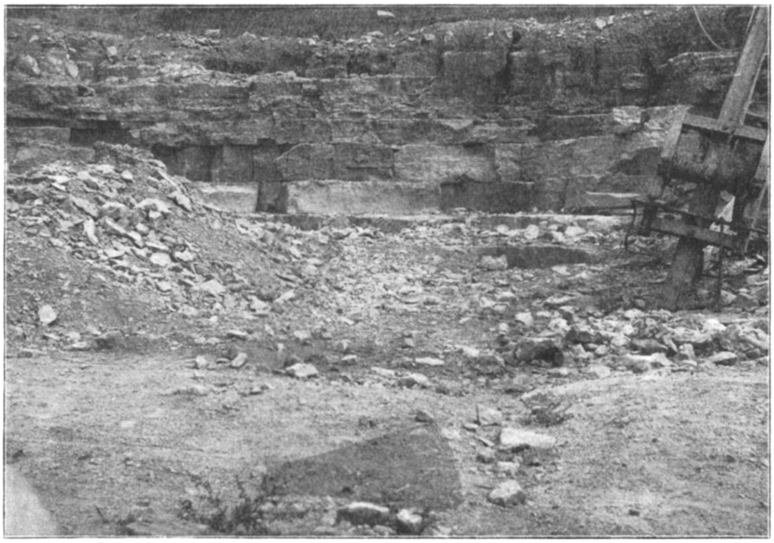
[1] Phil. Mag., Jan. 1900, p. 43.



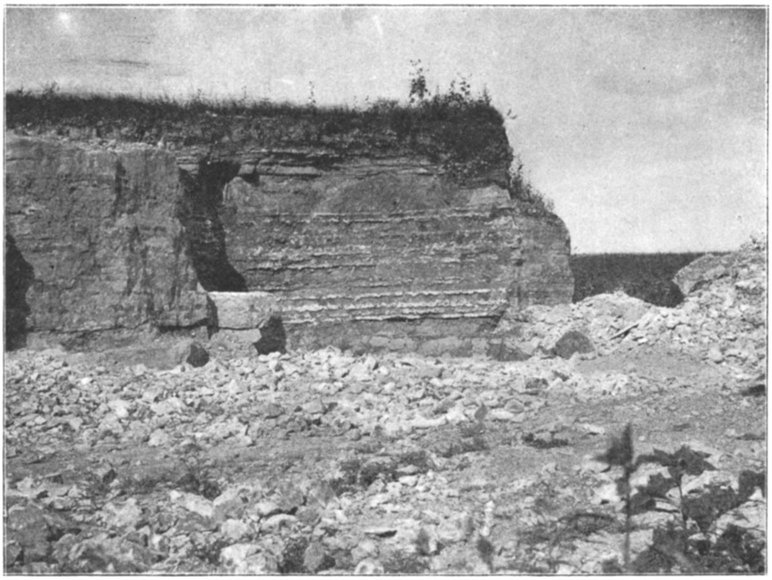


A Geological Section of the Nebraska Permian from Beatrice South and East to the Kansas Line.

[To be inserted between pp. 356 and 357, May–June number, 1899.]



LIMESTONE QUARRY ABOVE FLORENCE FLINT. BLUE SPRINGS, NEB.



EXPOSURE OF FLORENCE FLINT IN A QUARRY EAST OF WYMORE, NEB.